4. Land Degradation and Agricultural Productivity

Agricultural productivity is affected by differences between countries in measures of average land quality (fig. 1.4). Results suggest that agricultural productivity would also be affected by changes in land quality within a given area over time (fig. 1.5). Testing this hypothesis has been difficult, however, because of the scarcity of data—both on changes in land quality over time and on the impacts that those changes have on productivity. In the absence of data on these and other factors affecting productivity, a wide range of estimates have been offered regarding the magnitude of losses in agricultural productivity at various scales.

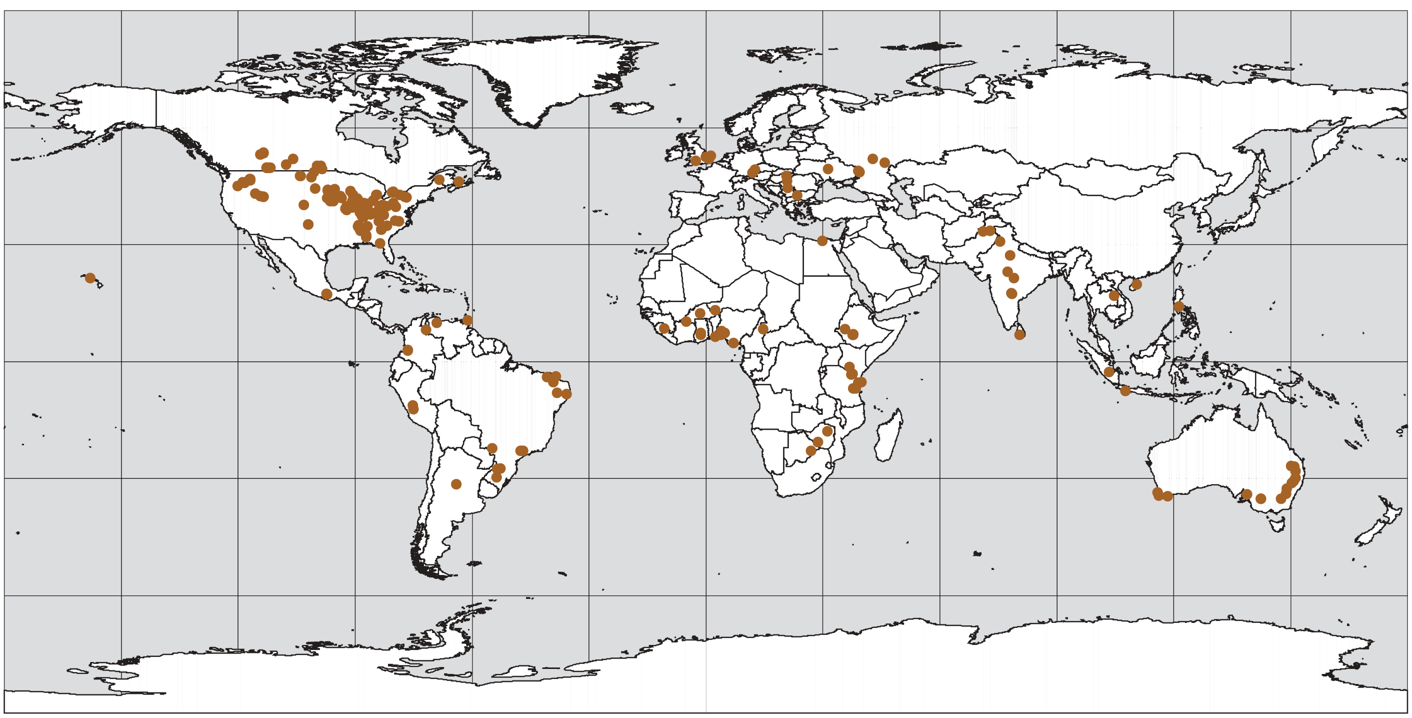
These studies, however, were based on models that were not described by their authors and therefore cannot be evaluated (e.g., Pimentel et al., 1995), data from a single country (e.g., Alt et al., 1989; Crosson, 1986; and Pierce et al., 1983), or inference from global opinion-based assessments of land degradation (e.g., Crosson, 1995a, 1995b). Since erosion and its impacts on productivity are extremely site-specific processes, dependent on environmental characteristics, management practices, and thus economic factors, site-specific data are costly to collect and global data are nonexistent. To overcome at least some of these limitations, den Biggelaar et al. (2001, forthcoming a and b) recently analyzed plot-level data from around the world on potential crop yield losses to soil erosion, using information on soil and climate characteristics to control at least partially for site-specific differences.

Evidence from plot-level studies

An extensive search of online databases and library catalogues identified 179 published plot-level studies from around the world that report changes in crop yields as a result of erosion. These studies contain a total of 328 records, each corresponding to a unique combination of crop, soil, and experimental method. These records represent a total of 38 crops on 9 soil orders in 37 countries (fig. 4.1).

The distribution of published research on soil erosion and crop yields is highly skewed with respect to the

Figure 4.1—Plot-level study sites



Source: ERS, based on data from den Biggelaar et al. (forthcoming a).

scope of agricultural production and land degradation (table 4.1). Of the 328 records identified, 197 (60 percent) represent experiments conducted in North America (the United States or Canada), but only 14 (5 percent) represent experiments conducted in Asia, which contains over a third of the world's cropland and degraded cropland, nearly half of the world's cereal production, and over three-quarters of the world's agricultural labor force. North American shares of each of these indicators are less than one-fifth. Africa and Oceania are well represented in proportional terms, at least at the aggregate level, while Europe and Latin America are under-represented with respect to most of the selected indicators. Even within regions, records tend to be highly concentrated, often in areas that are relatively productive but not necessarily particularly sensitive to erosion.

In the absence of long-term time-series data recording yield changes as erosion actually occurred on study plots, the studies used several generally accepted methods (Lal et al., 1998) to estimate yield effects of topsoil loss associated with erosion. About 35 percent of records compared yields on differentially eroded plots on a given soil. Another 29 percent involved mechanical removal or addition of topsoil, while 22 percent involved measurement of actual topsoil depth. Other studies compared yields across management practices associated with differential rates of erosion (e.g., conservation tillage and contour plowing); these studies are excluded from further consideration to avoid confusing the effects of changing practices with the effects of erosion per se. Records including multiple levels of an input (e.g., fertilizer) within a single management practice are retained, resulting in a total of 484 experiments for the 38 crops.

Crops represented in the plot-level studies include pasture and fodder crops, vegetables, and other high-value crops (such as tea), but the majority involved grains, pulses, and root crops. Den Biggelaar et al. analyzed six crops—maize, wheat, soybeans, sorghum, millet, and potatoes—that together accounted for three-quarters of the experiments conducted.

Mean yields and yield losses per ton of soil erosion were calculated across soils for each crop and region (table 4.2). Note that yield losses may accelerate, remain constant, or decelerate as soil erodes, depending on soil type and other factors (as in the hypothetical relationship depicted earlier in figure 1.4). Evidence suggests that accelerating losses are characteristic of many temperate soils, while decelerating losses are characteristic of many tropical soils (Lal, 1998a). Recognizing that yield losses cannot accelerate or remain constant indefinitely, and lacking sufficient data to estimate precise functional forms for each crop, soil, and region, a constant percentage change in yields is assumed, corresponding to the case where absolute yield losses decelerate as soil erodes. While this would certainly be an oversimplification over the long term, it should not introduce unreasonable bias for incremental losses of soil and yields over the shorter term.

In most cases, mean yield losses range between 0.01 percent and 0.04 percent per ton of soil loss. Percentage declines are generally lowest in North America and Europe, due in part to the fact that most experiments in those two regions were conducted on alfisols and mollisols, which are relatively abundant in temperate regions.[3] (Losses tended to be higher on oxisols, ultisols, and vertisols, which are relatively abundant in other regions, and where many studies in the other regions were done.) Lower percentage losses in North America and Europe are also due in part to higher mean yields in those regions due to higher levels of inputs (such as fertilizer). In one case (potatoes in North America), percentage losses were substantially greater, and in another case (soybeans in Asia), the mean yield on eroded plots was actually higher than the mean yield on uneroded plots. Two of the three North American potato experiments reported soil losses in tons rather than centimeters, as in the experiments for other crops and regions; it is possible that these yield loss estimates are biased due to different assumptions regarding soil bulk density. (We assumed a bulk density of 1.5 tons per cubic meter for all soils and regions.) A single experiment drove the average increase in Asian soybean yields; if data from that experiment were excluded, average yields for Asian soybeans would have declined 0.01 percent per ton of soil erosion.

Boardman (1998) cautions against uncritical extrapolation from plot-level data, describing the example of studies reporting a European-average erosion rate based ulti-

[3]**Alfisols** are soils with neutral pH and high in bases that form under forest or savanna vegetation in climates with seasonal moisture deficits, and predominate in the corn-growing areas of North America and northern Europe (Soil Conservation Society of America, 1982; Soil Survey Staff, 1998; Lal, 2003). **Oxisols** are highly weathered and leached mineral soils with low pH and low base concentration that predominate in the humid tropics of South America and Central Africa. **Ultisols** are less weathered than oxisols, but with low pH and low base concentration such that permanent cultivation is not possible without fertilization, and predominate in the southeastern United States and Southeast Asia. **Mollisols** are soils characterized by decomposition and accumulation of large amounts of organic matter, and predominate in the wheat-growing areas of North America, the former Soviet Union, and temperate South America. **Vertisols** are dark, nutrient-poor soils of the semiarid and arid regions of the tropics and subtropics; they have a high clay content and swell when wet and crack when dry, and predominate in parts of South Asia and the Sudan.

mately on data from 12 small test plots outside Brussels. The studies described by Boardman overlook the site-specific variation in characteristics of the sample (test plots) relative to the population (of all cropland in Europe). Yet limited data on site-specific characteristics are precisely what make careful extrapolation so difficult. The present analysis runs similar risks, not only in terms of extrapolating from plot-level data on yield losses per unit of soil loss (as described earlier) but also in generating the estimated erosion rates that are necessary

Table 4.1—Geographic distribution of plot-level studies relative to selected agricultural indicators

Region	Plot-level studies	Cropland (1999)	Degraded cropland (1990)	Agricultural population (1999)	Cereal production (2000)
	# of records	*Million hectares*	*Million hectares*	*Million people*	*Million tons*
World	328	1,491	562	2,575	2,049
Africa	52	202	121	431	112
Asia	14	544	206	1,957	987
Europe	17	308	72	65	384
Latin America	28	156	92	110	139
North America	197	225	63	7	395
Oceania	20	53	8	6	31
	% of world total				
Africa	16	14	22	17	5
Asia	4	36	37	76	48
Europe	5	21	13	3	19
Latin America	9	10	16	4	7
North America	60	15	11	<1	19
Oceania	6	4	1	<1	2

Note: "Degraded" refers to cropland that is classified in the GLASOD survey (Oldeman et al., 1991) as lightly, moderately, strongly, or extremely degraded due to biological, chemical, and physical degradation. Erosion accounts for 84 percent of total degraded area, and water-induced erosion accounts for 67 percent of total erosion in the GLASOD survey.
Sources: FAOSTAT (11Jul2001), Scherr (1999), den Biggelaar et al. (forthcoming a).

Table 4.2—Mean loss in annual yield per ton of soil erosion

Region	Crop	Experiments	Mean yield	Mean yield loss per ton of soil erosion	
		Number	*Tons per hectare*	*Kg per hectare*	*% of mean yield*
Africa	Maize	42	2.6	0.9	0.03
Asia	Maize	4	1.7	0.7	0.04
	Millet	2	0.3	0.1	0.03
	Soybeans	4	0.9	-0.5	-0.01
	Wheat	4	3.0	0.7	0.02
Australia	Potatoes	2	54.1	3.6	0.01
	Wheat	16	1.2	0.5	0.04
Europe	Millet	2	0.3	0.1	0.02
	Potatoes	2	11.4	0.6	0.00
	Soybeans	1	0.6	0.1	0.02
	Wheat	8	3.5	0.2	0.00
Latin America	Maize	15	2.9	1.4	0.05
	Potatoes	1	20.2	0.7	0.00
	Soybeans	4	2.1	0.6	0.03
	Wheat	1	2.1	0.4	0.02
North America	Maize	131	6.2	0.6	0.01
	Potatoes	3	30.5	127.0	0.42
	Sorghum	17	4.2	0.1	0.00
	Soybeans	43	2.1	0.3	0.01
	Wheat	64	2.6	0.4	0.01

Note: Some studies report multiple experiments.
Source: den Biggelaar et al. (forthcoming a).

to estimate annual yield losses (as described in the following sections). Recognizing these risks, this analysis attempts to control at least partially for such variation by incorporating spatial data on soil and climate characteristics and crop production areas.

Extrapolation using GIS data on land cover and erosion vulnerability

Estimating annual erosion-induced yield losses requires information on the rate at which soil is being lost to erosion. Such information is scarce, because accurate data are limited to a very few locations where long-term experiments have been conducted. Wider inference from more broadly available measures (such as soil type and climate patterns) is limited by the dependence of erosion on highly location-specific factors, such as slope, vegetative cover, precipitation intensity, and land management practices. Despite these limitations, broad inferences provide an approximation of the erosion rates needed to translate relative yield losses per ton of soil loss to annual yield losses due to erosion.

To estimate erosion rates by crop, soil order, and region, den Biggelaar et al. began with the digital map of soil orders compiled by Eswaran et al. (1997) based originally on FAO's Digital Soil Map of the World. Combining associated information on inherent soil properties (including soil depth and soil moisture regimes) with climate data, Eswaran et al. (2001) constructed a spatially referenced scale of vulnerability to water-induced erosion. (Note that water erosion accounts for 67 percent of GLASOD's global eroded area, and 56 percent of the 1997 NRI's estimate of soil erosion in the United States—with wind erosion accounting for the remainder.) Each of the five classes of this scale (depositional, low, medium, high, and very high) corresponds to a range of predicted annual erosion rates, with midpoints of 0.0, 9.3, 14.3, 17.2, and 25.8 tons per hectare, respectively.

To link these erosion rates with yield losses by crop, it was necessary to estimate spatially referenced crop production areas. (Actual crop production areas are reported annually at the national level by FAO, but these are not spatially referenced or identified with respect to soil type.) Potential crop production areas were identified for each crop based on crop-growth requirements and spatially referenced data on climate and soil characteristics.

Estimated erosion rates were then overlaid with soil orders and potential crop production areas to generate weighted-average annual erosion rate estimates for each crop area, soil order, and region (table 4.3). Estimated erosion rates vary widely by crop production area, soil,

Table 4.3—Estimated potential erosion rates by region, crop, and soil order

Region	Crop	Alfisols	Inceptisols	Mollisols	Ultisols	Mean
				Tons per hectare per year		
Africa	Maize	14.1	18.8	16.6	12.0	13.7
Asia	Maize	12.6	18.9	13.7	15.1	15.1
	Millet	14.1	11.4	17.2	14.5	14.5
	Soybeans	12.2	13.5	12.5	16.8	14.9
	Wheat	11.0	18.4	13.3	15.3	14.3
Australia	Potatoes	12.1	22.4	15.6	7.0	12.5
	Wheat	12.3	22.6	15.7	14.0	15.1
Europe	Potatoes	10.7	18.1	10.6	0.7	8.9
	Millet	13.6	11.0	14.3	12.1	10.8
	Soybeans	12.3	10.6	12.0	16.7	11.5
	Wheat	5.4	19.2	10.6	8.1	9.1
Latin America	Maize	14.4	19.2	14.3	13.1	14.0
	Potatoes	10.3	19.9	14.5	14.3	12.4
	Soybeans	14.4	14.1	14.4	15.7	13.8
	Wheat	11.0	21.3	14.3	15.4	13.2
North America	Maize	11.4	24.0	13.9	16.7	15.0
	Potatoes	11.1	11.6	13.3	15.0	8.7
	Sorghum	13.5	14.0	12.9	14.3	13.1
	Soybeans	10.7	14.5	14.5	16.8	14.3
	Wheat	10.7	14.3	13.2	15.0	12.1

Note: Mean erosion rates are calculated across all soil orders, including those not reported here.
Source: Eswaran et al. (various).

and region but range in most cases between 12 and 15 tons per hectare per year (corresponding to approximately 0.8-1.0 mm per year). Estimates tend to be highest on inceptisols, in some cases above 20 tons per hectare per year, because these soils are highly susceptible to erosion, particularly in sloping areas with intense rainfall and low water-infiltration capacity. Estimated rates for North America are typically higher than the average rate reported in the 1997 NRI for all U.S. cropland (10.3 metric tons per hectare), perhaps because the NRI seeks to account (however imperfectly) for the management practices actually chosen by farmers.

Annual losses in yields and production

Annual yield loss rates are estimated by multiplying the percentage yield loss per ton of soil loss (for each crop and region, averaged across soil types) by the estimated annual erosion rate for each crop, soil order, and region. These loss rates are then combined with estimates of total production to generate estimates of total production lost to water-induced erosion.[4]

Not surprisingly, given variation in relative yield losses per ton of soil loss and variation in estimated erosion rates, annual yield losses vary widely (table 4.4). Maize yield losses range from an average of 0.15 percent per year in North America (due to a combination of low relative yield losses and moderate erosion rates in major production areas) to 0.94 percent per year in Latin America (due to higher relative yield losses and higher erosion rates in many areas). Yield losses are generally lower for sorghum and millet, ranging from 0.06 percent for sorghum in North America (where percentage yield losses are near zero on all soils) to 0.51 percent for millet in Asia. Annual wheat yield losses are below 0.30 percent, except in Australia, where they average 0.67 percent.

Annual potato yield losses were 0.01 percent in Latin America and 0.12 percent in Australia, driven in each case by low relative yield losses. Mean relative yield losses from the three records in North America are much higher, generating annual yield loss estimates of 3.98 percent despite moderate erosion rates. Average soybean yields increased with erosion in Asia, driven by the results of a single study on vertisols; soybean yield losses elsewhere are relatively uniform, averaging between 0.22 and 0.33 percent annually.

To summarize erosion-induced yield losses across crops at regional and global levels, losses are weighted by total production levels (FAO, 2000) and 2000/01 commodity prices (USDA, 2001). (Prices per ton were $72.83 for maize, $72.75 for millet, $180.04 for soybeans, $93.96 for wheat, $129.00 for potatoes, and $64.96 for sorghum.) Results are presented as regional subtotals in table 4.4. Average annual losses in the value of production of the crops studied are lowest in Europe, at 0.04 percent, where higher loss rates in millet and soybeans are offset by lower rates on more economically important potatoes and wheat. Average annual loss rates are highest in Australia (0.61 percent) due to high relative yield losses in wheat. Losses in Africa, Latin America, and North America range from 0.45 to 0.49 percent per year. (North American losses would fall to 0.17 percent if potatoes were excluded.) Losses in Asia average 0.24 percent per year, with higher loss rates for maize and millet offset by smaller losses for wheat and gains for soybeans.

Finally, aggregating across regions for each commodity generates estimated annual losses in the global value of crop production that range from 0.06 percent for sorghum and 0.08 percent for soybeans to 0.60 percent for potatoes. Intermediate loss rates are found for wheat (0.20 percent), maize (0.42 percent) and millet (0.48 percent). Aggregating across regions and crops generates a global average annual erosion-induced loss of 0.30 percent in the value of crop production.[5]

Lessons from plot-level studies

These results need to be interpreted with caution. First, estimates of erosion and yield response are highly sensitive to site-specific environmental and economic characteristics, which are not fully addressed by the spatial

[4]Total production was derived by multiplying estimated crop production areas by estimated yields for each crop, soil order, and region. Estimated potential production areas exceeded actual production areas reported by FAO for 1998-2000 for each crop and continent (FAO, 2000), because they were based only on biophysical potential, regardless of economic criteria, and many areas are capable of growing a variety of crops. Potential production areas were scaled to actual totals by overlaying them with 1-kilometer-resolution satellite data (USGS, 2000) on the location of cropland and then scaling them up or down to match harvested areas reported by FAO. In most regions and for most crops, production is concentrated on alfisols, mollisols, ultisols, and inceptisols, which represent an estimated 86 percent of the total acreage reported by FAO for these crops. Estimated crop yields were similarly scaled to FAO-reported yields for each crop and region.

[5]Estimated annual losses are based on the sum of regional production totals calculated from our estimates of production areas and yields, and represent 23 percent, 49 percent, 60 percent, 89 percent, 97 percent, and 100 percent of the average annual world production reported by FAO for 1998-2000 for sorghum, millet, potatoes, maize, wheat, and soybeans, respectively (FAO, 2000). The remaining shares of those crops are produced in regions that were excluded from our estimates because we found no erosion-productivity studies for those crops in those particular regions.

controls in the present research. Second, these estimates are indicative of the *potential* scale of yield losses to erosion; actual losses will be smaller to the extent that farmers mitigate the impacts of erosion through changes in input levels and/or management practices. In terms of figure 1.5, potential losses correspond conceptually to the difference in yields over time between case (a) and case (d), while actual losses are represented by the difference between case (a) and whichever degradation rate is actually chosen or accepted by farmers. (This issue will be explored in the next section.) Third, these estimates represent impacts only for the selected crops in regions where relevant plot-level studies were found. If proportionate impacts were assumed to occur on the selected crops in other regions, the estimated total value of losses for these crops would rise from $439 million to more than $500 million. Furthermore, the six selected crops represent only a fraction of the total value of global crop production; if impacts on other crops occur in proportion to their value, estimated losses would rise about fourfold, to $2 billion. Fourth, these estimates represent impacts only of water-induced erosion; NRI and GLASOD data on the relative extent of wind erosion suggest that adjusting for similar impacts from wind-

Table 4.4—Estimated value of potential annual erosion-induced production losses by crop and continent

Region	Crop	Total production[1]	Production loss	Value of total production[2]	Value of production loss[2]	Production loss
		Thousand tons per year		*Million $ per year*		*% per year*
Africa	Maize	41,198	202	3,000	15	0.49
	Subtotal	--	--	3,000	15	0.49
Asia	Maize	162,289	961	11,820	70	0.59
	Millet	12,693	64	923	5	0.51
	Soybeans	23,493	-254	4,230	-46	-1.08
	Wheat	254,338	740	23,898	69	0.29
	Subtotal	--	--	40,870	98	0.24
Australia	Potatoes	1,872	2	241	<1	0.12
	Wheat	22,739	152	2,137	14	0.67
	Subtotal	--	--	2,378	15	0.61
Europe	Millet	1,060	2	77	<1	0.23
	Potatoes	136,832	51	17,651	7	0.04
	Soybeans	2,3134	5	417	1	0.22
	Wheat	181,517	74	17,055	7	0.04
	Subtotal	--	--	35,200	15	0.04
Latin America	Maize	74,608	704	5,434	51	0.94
	Potatoes	16,281	2	2,100	<1	0.01
	Soybeans	55,426	184	9,979	33	0.33
	Wheat	21,720	58	2,041	5	0.27
	Subtotal	--	--	19,554	90	0.46
North America	Maize	259,122	399	18,872	29	0.15
	Potatoes	25,903	1,031	3,341	133	3.98
	Sorghum	13,811	8	897	1	0.06
	Soybeans	77,879	191	14,021	34	0.24
	Wheat	90,360	96	8,490	9	0.11
	Subtotal	--	--	45,622	206	0.45
Total[3]	Maize	537,217	2,266	39,126	165	0.42
	Potatoes	180,888	1,086	23,335	140	0.60
	Millet	13,752	67	1,000	5	0.48
	Sorghum	13,811	8	897	1	0.06
	Soybeans	159,110	126	28,646	23	0.08
	Wheat	570,675	1,120	53,621	105	0.20
	Total	--	--	146,625	439	0.30

[1] Production data from FAO (2000).
[2] Prices based on projected 2000/01 crop prices from USDA (2001).
[3] Totals fall short of global total production of these crops because they exclude crop-region combinations for which no plot-level studies were found (e.g., wheat in Africa).
Source: den Biggelaar et al. (forthcoming b).

induced erosion would raise estimated losses by an additional 50 percent, to $3 billion, and still further for other forms of soil degradation. (This figure represents about 0.4 percent of the total value of global crop production in the mid-1990s (Wood et al., 2000).) Fifth, these estimates exclude offsite impacts of soil erosion, both on productivity (e.g., via deposition of fertile sediments downstream or via wider economic impacts on income, growth, and food security) and on environmental quality. Evidence suggests that these impacts may be substantially larger than onsite effects.

Cautions notwithstanding, these results have important implications for the ongoing debate on erosion and its impacts on productivity. First, they are consistent with the lower range of previous estimates, similar in percentage terms to that of Crosson, and much lower in both relative and absolute terms than the Pimentel et al. figure ($27 billion per year for the United States alone). This does not mean that erosion-induced yield losses are unimportant—just that they have historically been masked by growth in yields (which has averaged over 2 percent per year in recent decades for the world as a whole) due to improvements in technology and increases in input use. Such increases may become more difficult to sustain in the future, with projections that yield growth will slow to about 1 percent per year over the next few decades.

Second, these results indicate areas where high erosion rates and/or high relative yield losses per ton of soil loss generate potential annual yield losses well in excess of global or regional averages. Of special concern is the wide disparity in experimental research relative to the potential severity of erosion impacts, particularly the scarcity of studies in developing regions where yields are especially sensitive to erosion and farmers are especially sensitive to losses in income. (Information on farmer responses to erosion and other forms of degradation is also relatively scarce in developing regions.) Erosion impact studies are relatively scarce for all crops in Asia and for crops other than maize in Africa and Latin America. For maize, yield losses (in percentage terms) are three to five times as high in the developing regions as they are in North America.

Third, these results suggest the importance of additional spatially referenced research on erosion, yield impacts, and, especially, farmer responses, to better understand how potential impacts on yields may translate into actual impacts on agricultural productivity.

Finally, these results indicate that, at least at global and regional scales, potential yield losses are generally small enough that private incentives to reduce erosion may be weak. This strengthens the case for policy measures to address erosion's other (and perhaps more significant) effects: offsite impacts, both economic and in terms of sedimentation's effect on water quality, flooding, irrigation costs, and environmental quality.

As noted, these are potential impacts assuming no changes in other inputs, but we know that farmers will in general have an incentive to respond in ways that reduce or avoid such impacts. In fact, Crosson suggests the small actual productivity losses he estimates indicate that private incentives are strong enough to mitigate potential losses that could conceivably be somewhat larger. Private incentives are indeed critical to actual outcomes. But private incentives are sensitive to economic factors as well as biophysical conditions, and data on economic factors are as scarce as data on biophysical conditions. We examine private incentives next.